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Article

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Price-based Demand-side Management Model for Industrial and Large Electricity Consumers

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ABSTRACT

This article discusses a price-based demand-side management (DSM) model for industrial and large power consumers. We have analyzed various factors affecting the improvement of energy efficiency on a national scale as well as at the level of select enterprises and large electricity consumers and have concluded that DSM is one the key areas of increasing energy efficiency, with the price-based consumption as its core element. Using the Russian electricity market as a model example, this article investigates the formation of all cost components of the ultimate power price – electricity, capacity and transmission services. Based on the results of the power cost component analysis, the article concludes that the price-based DSM can be applied to all price components and identifies areas and hours for optimal DSM in order to minimize the purchase price of electricity, while maintaining the aggregate demand. Based on the identified specifics, we have developed a price-based DSM model for industrial and large electricity consumers, taking into account the factors that limit the required management of the demand. The suggested model can be adapted for retail and wholesale electricity customers alike. Given that the Russian electricity market is largely similar to other power markets, such as Nord Pool, EPEX, Powernext, PJM, New England ISO, etc., the suggested management methods can be adapted for application in other countries. The article also discusses a communication strategy for the suggested model. The results of this research have high theoretical and practical importance and can be used in power purchase-related activities of industrial and other large consumers in any country where the electricity is priced according to market principles.

Keywords: Demand-side Management of Electricity, Price-dependent Consumption, Energy Costs, Operational Efficiency, Energy Efficiency, Production Scheduling

JEL Classifications: Q43, P18, L94

1. INTRODUCTION

The ongoing depletion of global hydrocarbon reserves used for the production of energy resources coupled with the continuously increasing electricity consumption in the developed and, especially, developing economies of the world lead to the ever increasing cost of energy in global and national energy markets. Figure 1 shows total energy consumption and electricity domestic consumption in the world in the period 1990-2017, and Figure 2 shows consumption price indices of different energy resources among the OECD countries in the period from 1997 to 2017.

As can be seen from Figure 1, over the past 26 years, the global total energy consumption has increased by 58%, and the global electricity consumption has increased by 2.08 times. Given the high growth pace of many economies and, in particular, in the Asia Pacific region, total energy consumption will continue the current trend. Also, as can be seen from the curves in Figure 2, the prices of different energy recourses have been growing likewise over the past 20 years, except for the decline in 2012 due to a market situation. And given the upward trend of the energy consumption, the prices will continue to grow.

Given the widespread use of energy resources in the activities of a modern community and their high share in the cost of industrial

Figure 1: Total energy consumption and electricity domestic consumption in the world for the period 1990-2017 (Enerdata, 2017)

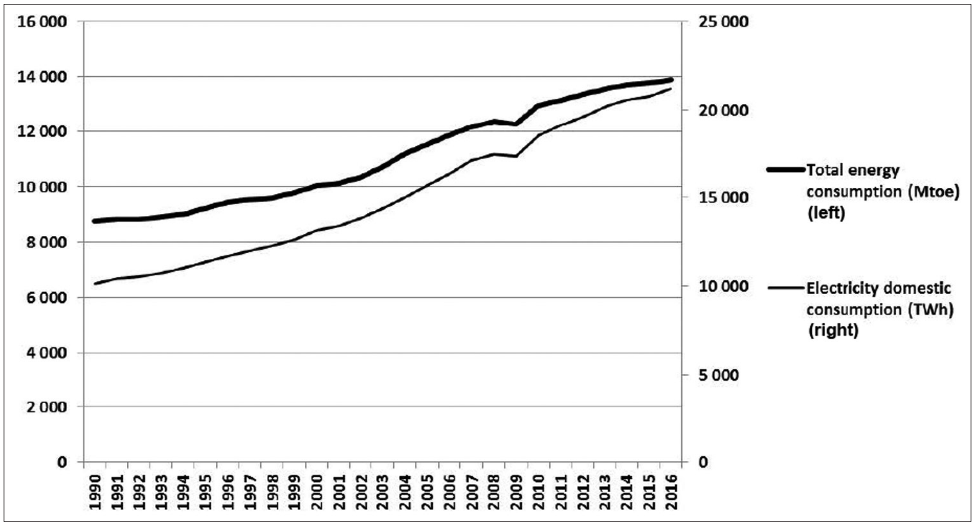
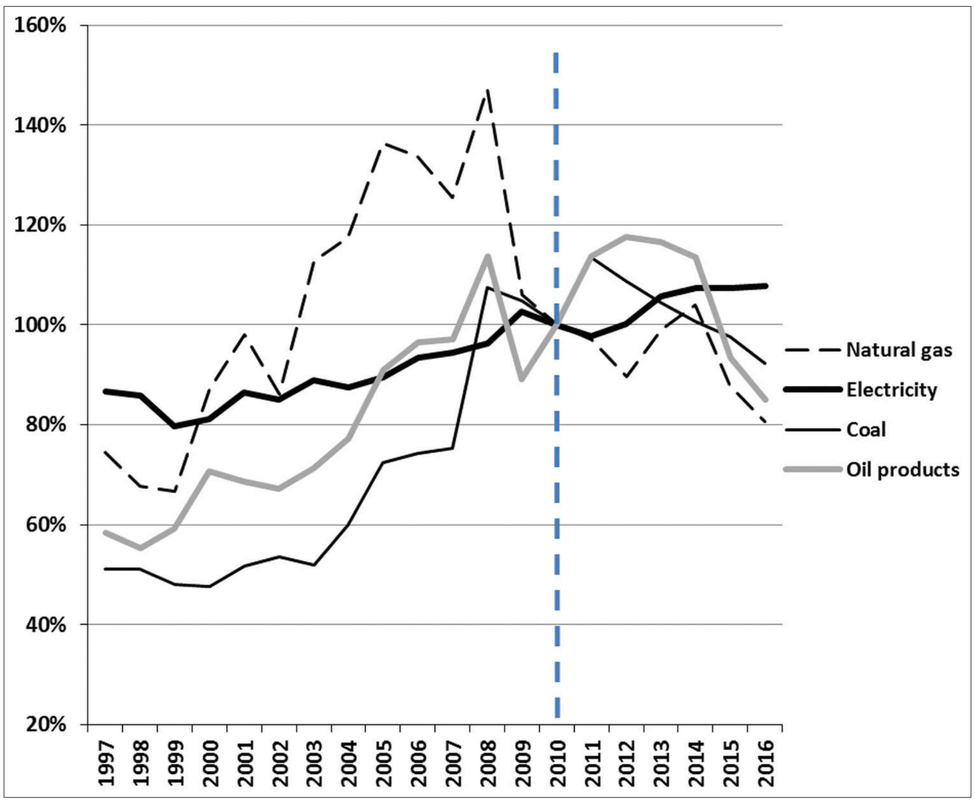


Figure 2: End-use price indices for different energy resources among the OECD countries for the period from 1997 to 2016 (International Energy Agency, 2016)



products, one of the global trends in a new high-tech world over the past 10-15 years has been a strong focus on energy saving and efficiency. The implementation of an energy saving policy allows, without heavy investments, to give momentum to social and economic development at the national level (Leslie et al., 2012).

Among the key effects of an energy efficiency policy at the level of the national economy, are:
- Improving the competitiveness of products by reducing the price of purchased energy in their cost structure
- Cost reduction along all budget areas
- Improving the energy security of a national economy
- For hydrocarbon exporting countries – increasing treasury incomes
- Preservation of domestic hydrocarbon reserves
- Introduction of innovations.

Therefore, energy saving and efficiency are a pivotal area of a national policy and a core element of a national strategy for many developed and developing economies of the world (British Petroleum, 2017).

Energy saving and efficiency have a special importance for the Russian economy due to several reasons that are summarized in Table 1.

Since 2009, after the adoption of the Federal Law "On Energy Saving and Improving Energy Efficiency and Amending Certain Legislative Acts of the Russian Federation," Russia has been implementing energy saving and energy efficiency mechanisms across all levels of the economy. However, as shown in Figure 3, the current energy intensity of the Russian GDP significantly lags behind the targets set by the national initiative called "Energy Saving and Improving Energy Efficiency by 2020."

Electricity takes a special place among all energy resources which people use (International Energy Agency, 2017). It is the most common energy carrier in the world due to its wide-spread production, simplicity and low cost of transportation over long distances, distribution to a large number of consumers at the same time, applicability in any climate, and its ability to convert to other types of energy, such as mechanical, thermal and light energy. Moreover, most energy resources, including natural gas and coal, are exploited in order to produce electrical energy. Therefore, improvement of electricity efficiency leads to an increase in the efficiency of the using these commodities. Electricity efficiency is therefore the highest priority on the energy agenda of any country in the world.

Table 1: Drivers of energy efficiency in Russia

Driver	Description
Technological	Many industrial consumers in Russia operate outdated energy-intensive equipment compared to other countries of the world
Structural	A high share of energy consumption by industry compared to other countries of the world
Climate	Harsh climate conditions in Russia result in high energy expenses for heating and lighting
Geographical	Long distances and geographical extent result in higher energy costs for transportation
Fiscal	High dependence of the national budget's revenues on hydrocarbon exports
Economic	Inflated energy costs put a significant burden on the production costs of Russian manufacturers, which is especially noticeable in the times of economic downturn
Environmental	High emissions in the process of extraction and processing of energy resources

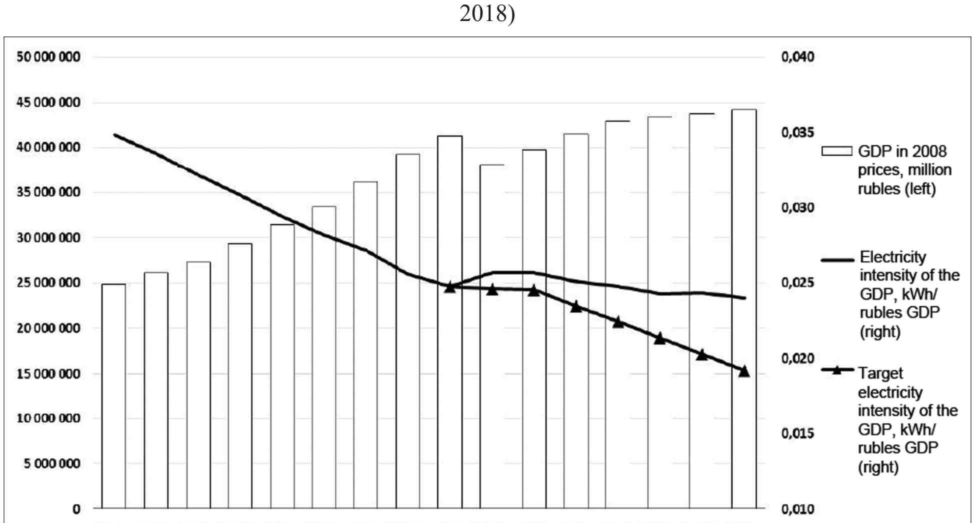
The increased interest to the problem of energy efficiency has significantly augmented the investments in energy-saving R&D and production. New technological trends in the energy industry have triggered institutional and structural changes in the management and processing of energy resources, with the new functions of the grids (Volkova et al., 2011) and new economic and management fields appearing that contribute to the gradual reduction of system-wide costs at all levels of the production chain in the industry (Loginov and Loginov, 2012).

The formation of new economic fields manifests itself as a new type of relations between electricity generators and consumers, taking the form of a wholesale and a retail power markets. In the energy markets, electricity is purchased in real time, and market operators actually control the amount of generation and consumption between all market players at the same time, including estimation of the supply and demand according to consumption parameters.

New management fields are manifested in the form of new technologies being implemented for scheduling and management of the power processes from the national level to the level of the ultimate industrial and household customers (Chiu et al., 2013). The essence of the changes in the power management boils down to increasing energy consumption data at all levels and improving its use and communication. This, in turn, leads to new energy players appearing on the arena, such as metering market operators, and stepping up the role of other players in the circulation of energy resources.

Smart grids are one of the most striking manifestations of the impact that innovations can bring to the power industry (Kobets and Volkova, 2010; Carmoab et al., 2014). Smart grids build on

Figure 3: Dynamics of the target versus actual electricity intensity of Russia's GDP for the period 2000-2015 (Federal State Statistics Service, 2018)



the concept of a fully integrated, self-regulating and self-restoring electric power system that has a network topology and includes all generating sources, backbone networks (including interstate backbone power lines), local distribution networks and all types of power consumers controlled by a single communication network in real-time (IEEE Emerging Technology Portal, 2009). The smart grid concept has become a priority on the energy and innovations agenda of many global economies (Volkova and Salnikova, 2010). In the EU countries, smart grids develop under the Smart Grid European Technology Platform, and under the Energy Independence and Security Act in the USA (European Commission, 2006; Emec et al., 2013). In Russia, the process of implementing the smart grid policy is in the conceptual phase yet.

We believe that demand-side management (DSM) will come as one the most efficient methods for increasing energy efficiency as it has been successfully applied in many developed countries and demonstrates robust results.

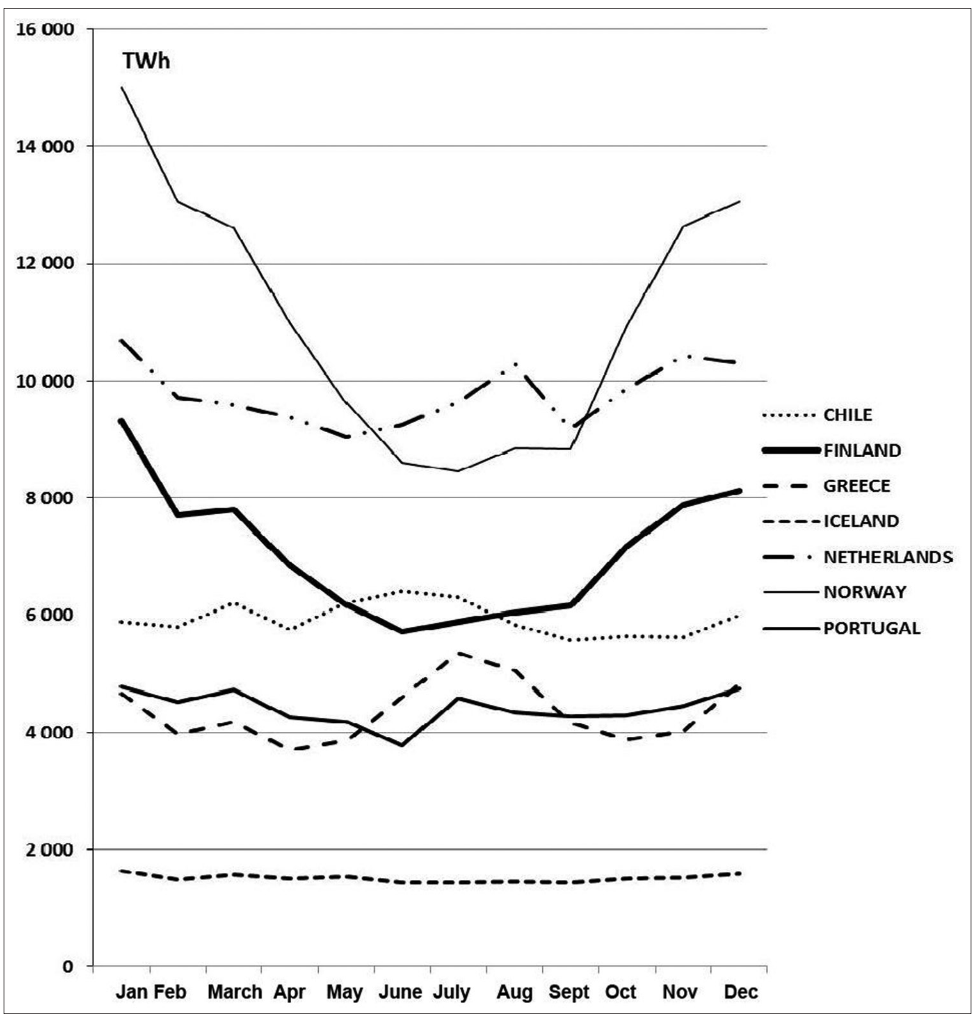
2. DSM

Management of the demand is an accepted concept that is used by energy providers and customers worldwide and it is called "demand-side management," or DSM (Lampropoulos et al., 2013). It may also be referred to as energy demand management (Government of United Kingdom, 2016) or demand-side response (DSR) (Torriti, 2015). The term DSM was introduced after the world oil crises that took place in 1973 and 1979 (Smith, 2006). These energy crises primarily affected the US economy and revealed a real threat to energy security at the national level (U.S. Department of State, 2012). "Demand-side management" was officially introduced by the US Electric Power Research Institute in the 1980s (Murthy et al., 2011; Balijepalli et al., 2011). In 1993, the International Energy Agency, which was formed by OECD member states after the "first oil shock" in 1974, laid the foundation for the global programs focusing on DSM technologies (International Energy Agency, 2018).

DSM is a pro-active form of economic interaction between electric power entities and end users, which provides mutually beneficial, cost-effective regulation of volumes and modes of energy consumption (Gitelman et al., 2013).

DSM aligns daily and annual demand schedules across regional and integrated power systems (Figure 4 shows an example of an electricity demand schedule), which, in turn, helps reduce costs in production, transportation and distribution of electricity and, ultimately, lower the electricity tariffs for customers. DSM

Figure 4: Hourly demand for electricity in various countries of the world in 2018 (the scale is preserved) (Eurostat, 2018)



generates a significant economic impact by reducing the purchase price for all customers within a grid (Dziuba and Solovieva, 2018).

The demand of different consumers and the energy system in general may vary greatly over short and medium periods of time, depending on a number of factors, including weather, daylight hours, production schedules, etc.

Figure 4 shows hourly electricity demand in different countries in 2018. As can be seen from the graph, annual demand in different countries differs both in terms of the general demand parameters and the demand curve during a year.

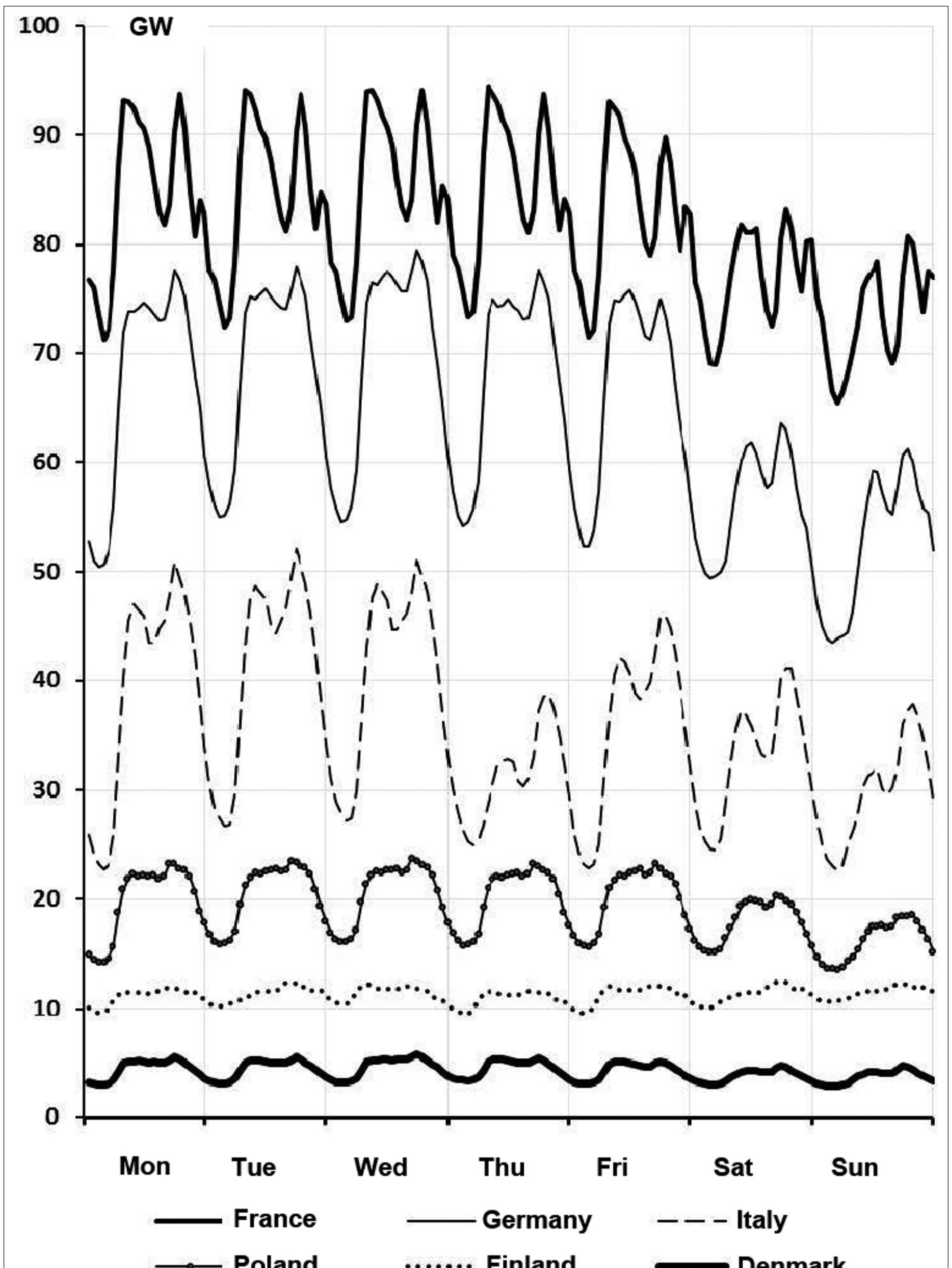
Figure 5 shows a graph of hourly demand in various countries of the world during a week in December 2018. As can be seen from the figure, hourly demand in different countries demonstrates volatility trends which are specific for each country. Figure 2 also shows significant differences between the demand levels during business days and weekends in different countries.

The difference in the demand volatility of different territorial entities depends on their specifics, including:

- Economic structure of a given territorial entity
- Industry sectors that electricity consumers come from
- Total electricity demand
- Climate and geographic specifics of a given territorial entity
- Other individual factors affecting the demand.

Demand curves of individual countries or territorial entities consist of total demand curves of all electricity consumers, including

Figure 5: Hourly demand during a week in different countries, December 2018 (the scale is preserved) (Eurostat, 2018)



industry, household, transport, construction, etc. Figure 6 shows sample demand curves of different types of industrial customers. As seen from the graphs, each customer has its own characteristic impact on the general demand in the local or integrated grids.

Generators adjust their schedules to the changing demand by generating more or less electricity. However, during peak hours, it is usually less efficient "peak" generators that supply the unmet demand, and the costs of using "peak" generators immediately affect the retail prices. Figure 6 demonstrates the pricing principle that is applied in Russian electricity spot market (the "day-ahead market") with a fluctuating demand. As can be seen from Figure 7, the purchase price of electricity changes proportionally to the fluctuations of demand parameters.

The uneven demand forces generators to build significant reserve capacity which is only used to meet short-term peak demand and is idle most of other time. The same is true about the grid infrastructure: Power lines are built to cover the demand volatility.

Table 2 outlines the effects which consumers can get from the DSM. Therefore, by aligning the demand generators and distributors bring down their costs, which ultimately translates into lower tariffs for customers within a grid. DSM impacts the economy at all levels, as illustrated in Table 3.

Obviously, the implementation of DSM is critical for the Russian economy from the strategic point of view because the demand volatility problem exists at all levels in any country – from a single enterprise to the national grid system in general.

DSM activities strive to optimize the demand to its most even level so as to decrease the use of peak generators.

DSM smooths out the peaks and falls of electric loads in the grid, thereby reducing the costs of generators as well as the costs for maintaining excessive capacity and preventing incidents in the grid (Solovieva and Dziuba, 2017).

DSM technology is being widely deployed in more than 30 countries around the world including the USA (Shariatzadeha et al., 2015), Canada (López et al., 2019), UK (Chilvers et al., 2017), the European Union, Germany (Emec et al., 2013), France (Jacquot et al., 2017), Australia (Marwan et al., 2011), Denmark (Pavani et al., 2017), Japan (Shiraki et al., 2016), Brazil (De Moraes et al., 2011), Turkey (Ayan and Emre, 2017), China (Albadi et al., 2007), Thailand, Vietnam, India, and Iran (Zeinaddini-Meymand et al., 2017).

A study of the existing DSM programs around the world has revealed common approaches and tools that are used to manage energy demand, such as: Use of energy-saving equipment, transition to renewable electricity, differentiation of electricity tariffs, etc. The difference is only in the scale of such programs, which is associated with the volume of funding and government support for DSM initiatives.

3. DEMAND RESPONSE

DSM is enabled through stimulating electric utility consumers to synchronously change their demand schedule of electricity consumption. The change in power consumption of an electric utility to better match the demand for power with the supply is called demand response.

According to the reports of the Federal Energy Regulatory Commission of the United States, the demand response is

Figure 6: Sample demand curves of different industrial customers

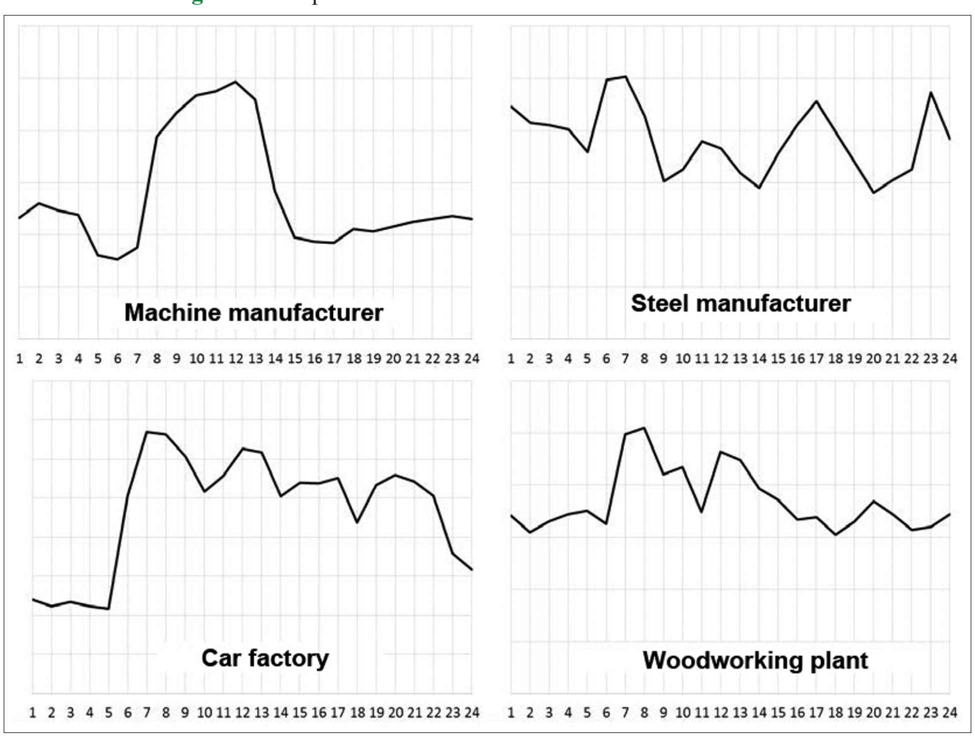


Figure 7: Example of the pricing principle of the Russian electricity spot ("day-ahead") market with the demand volatility (Shariatzadeha et al., 2015)

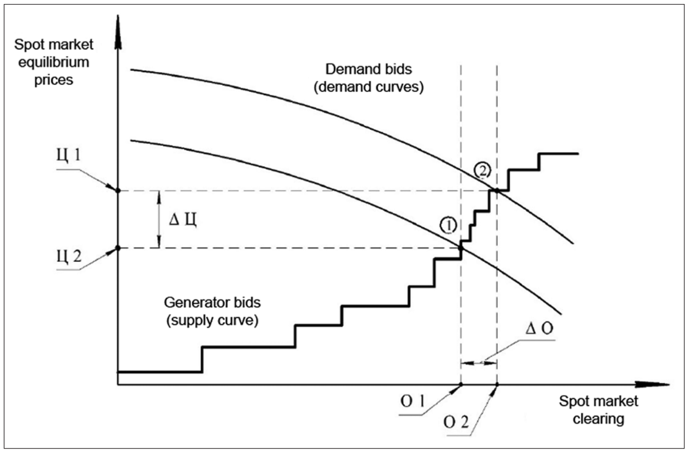


Table 2: Effects of the demand-side management at different levels

Management level	Effect
Generation	Increasing the stability of generation modes
	Reducing specific fuel consumption for electricity generation (Kobets and Volkova, 2010)
	Decreasing the required fuel reserves
	Decreasing the spinning reserve of generating capacities
	Decreasing the investments in the upgrade
Transmission	Decreasing the reserve of grid capacities
	Incident reduction
	Decreasing technological losses in the grid
Distribution	Release of capacities to connect new consumers
	Improving the quality of power supply
	Decreasing commercial losses in the distribution networks

defined as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." Demand response can also be defined as "a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions within the electricity system (such as peak period network congestion or high prices)."

Demand side is the activity of electric utility consumers when they change their consumption pattern by throttling their production rate or postponing some tasks that require large amounts of electric power until peak periods of the power system. Some customers may switch part of their consumption to alternate sources, such as small distributed generation systems.

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Table 3: Economic effects of demand-side management at different levels of the economy

Economic system level	Effects
Government	Improving energy security by freeing up additional generating capacity
	Improving the energy efficiency of a national economy by reducing the energy costs of all end consumers
	Decreasing the budget spending by reducing customer subsidizing
	Increasing budget revenues due to the release of energy fuel and its potential export (mostly, natural gas)
	Improving the environmental safety of energy industry by reducing emissions
Customers	Decreasing energy tariffs due to the aligning of the daily demand schedules and reducing transmission losses
	Improving the quality of electricity, which positively impacts the stability of energy-receiving equipment and the quality of products
	Increasing the availability of connection to electric networks due to the release of grid capacity
Power industry	Lower investments in the generation mix due to reduced demand
	Reducing fuel costs in generation by reducing fuel reserves
	Lower operating costs in generation due to the decreased supply obligation and longer service life of the generating equipment
	Lower investments in the grids due to freeing up transmission capacity and longer service life of the transmission and switching equipment
	Lower operating costs in the grids due to the decrease in necessary maintenance
	Reducing incident rate and increasing the service life of the grid equipment
	Improving the reliability of equipment at the national grid level
	Increasing the service life of equipment at the national grid level
Related industries	Lower prices for primary energy resources (coal, gas, fuel oil) due to reduced demand from the energy sector
	Growth of innovations (software and technologies) aimed at managing electricity demand on the side of industrial customers

Economic rationing system for electric power supply is a DSM system based on incentivizing consumers to manage their power consumption. Price incentives offer lower net unit pricing in exchange for reduced power consumption in peak periods. The direct implication is that users of electric power capacity not reducing usage during peak periods will pay “surge” unit prices.

Involuntary rationing is a DSM system accomplished via rolling blackouts during peak load periods with a view to prevent further demand surges.

Historically, DSR programs have focused on maximizing demand reduction which ultimately aimed at minimizing the cost of generating capacity. A modern DSR model aims at a more flexible change in the consumption pattern, taking into account the operation of variable renewable energy (VRE) units. VRE is the use of VRE units. VRE systems are based on generating electricity using the solar and wind energy. However, VRE sources are considered unstable as the natural conditions are prone to fluctuations.

Demand response may embrace a wide range of areas including energy efficiency, energy management at home and in buildings, distributed renewable resources and charging of electric vehicles.

4. PRICE-BASED DEMAND

Price-dependent demand is a model of flexible electricity consumption management in response to the price signals of the power market, aimed at minimizing electricity costs.

Price-based demand is a model for end-use customers to manage their electricity costs within the economic rationing system. The price-based demand is based on the economic incentives from the power system.

In most countries of the world, all electric power is sold and bought in the context of power markets which offer discrete pricing for the electricity. The electricity price generally reflects the demand and supply situation, enabling the customers to flexibly manage their power costs by adjusting their consumption patterns.

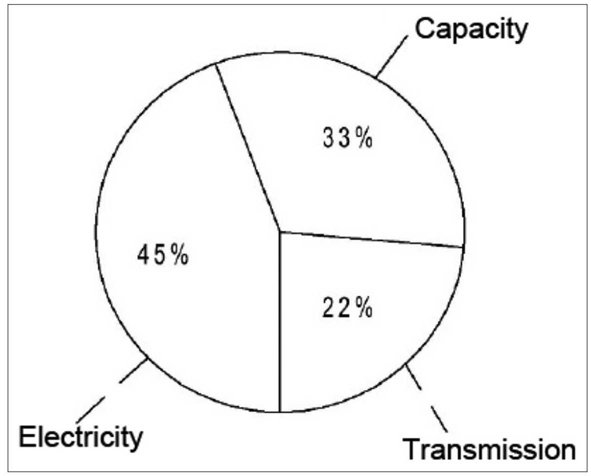
The price-based demand management on the side of industrial customers can actually bring down electricity costs without affecting the production rates. This economic effect is achieved due to the economically feasible redistribution of the production schedules and the associated electrical loads.

5. RESEARCH METHODOLOGY

The price of electric energy for industrial customers in Russia consists of three main components: electricity, capacity and transmission. Figure 8 illustrates the average structure of the electricity price for industrial customers in Russia.

The electricity and capacity prices are set through a competitive pricing mechanism, whereas the price of the power transmission services depends on adjustable price parameters.

Figure 8: The structure of the electricity price for industrial customers in Russia



While industrial customers can hardly impact the electricity market prices, they can certainly adjust their consumption patterns by adjusting production processes and putting on and off line their units which consume the most power.

From our point of view, the price-based demand management can actually impact all components of the power price, enabling customers to bring down their electricity costs.

5.1. The Electricity Component

The amount of obligation of an industrial consumer to pay for electricity, capacity and transmission is calculated individually according to the hourly electricity consumption in a given reporting month. The methodology for calculating the amount of obligations to pay for each price component has its own principles, rules and specifics.

The electricity payment obligation is calculated according to the hourly market prices on the day-ahead (spot) market and the corresponding amount of hourly electricity consumption. Figure 9 illustrates hourly prices on the spot power market. As can be seen from the figure below, the spot prices set for each hour have significant intraday volatility. The difference between the night hour prices and the daily peak prices may reach 2 times or more. Moreover, the spot prices differ between working days and weekends, which can also reach double value.

From our point of view, the price-based management of the hourly electrical loads should be accomplished through the redistribution of consumption from the periods with the highest price of electricity to the periods with economically reasonable prices, enabling industrial customers to save on their electricity costs by up to 50%.

The range of the price-based management should be defined according to the spot market forecasts.

Formula (1) is used to calculate the “electricity” component of the price, and formula (2) – the effect of the price-based management, which is calculated as the price difference before and after the demand management effort (2).

$$SW_m = \sum_m (W^t \times P^t_{spot}) + \sum_m P_{BM} \quad (1)$$

where,

SWm is the price of electrical energy purchased by an industrial customer in the month m

W^t is the rate of electricity consumption by an industrial customer in hour t

P^t_{spot} is spot market price in hour t

$\sum_m P_{BM}$ is the purchase price of electricity in the balancing segment of the wholesale power market.

$\sum_m P_{BM}$ is taken into account when the electricity is purchased on the wholesale market or in the event of the fifth or sixth price category in the retail market. We have also conducted extensive research regarding the management of energy costs in the sector $\sum_m Ц_{БР}$.

$$\Delta SW_m = SW_m - SW'_m \quad (2)$$

where,

ΔSW_m is the saving on electricity purchase costs due to the price-based demand management

SW_m is the cost of paying for electric energy before the application of price-based demand management

SW'_m is the cost of paying for electric energy after the application of price-based demand management.

5.2. The Capacity Component

The amount of obligation to pay for electric energy is calculated each month based on the hourly schedule of power consumption of each participant. The amount of obligation to pay is calculated as the average capacity consumed by an industrial customer during the hours that are daily peak hours in a local grid, on the working days of a given month. Daily peak hours of a given local grid are limited to the scheduled peak hours. Figure 10 illustrates the calculation of the obligation to pay the capacity for an industrial customer.

As can be seen from Figure 3, the amount of obligation to purchase capacity does not depend on the daily peak demand of the given customer, but rather on the daily peak hour of the grid as such. Daily peak hour of the grid is determined only for the working days of the corresponding month and always falls on one of the scheduled peak load hours (the blue zone on Figure 11).

Therefore, in order to reduce its obligation to purchase capacity, an industrial customer needs to shift its peak load hours to the hours that do not fall into the blue zone nor the grid's peak hours.

Prediction of the grid's peak hour with a fairly high probability can be accomplished using the historical data for the past few years.

The suggested approach allows industrial customers to reduce their capacity purchase costs by 10% to 80%. Formula (3) is used to calculating the capacity component of the power price, and formula (5) – the effect of the price-based demand management effort.

$$SP_m = VP_m \times TP_m \quad (3)$$

Figure 9: Example of hourly daily spot prices on a working day and a non-working day in July 2016

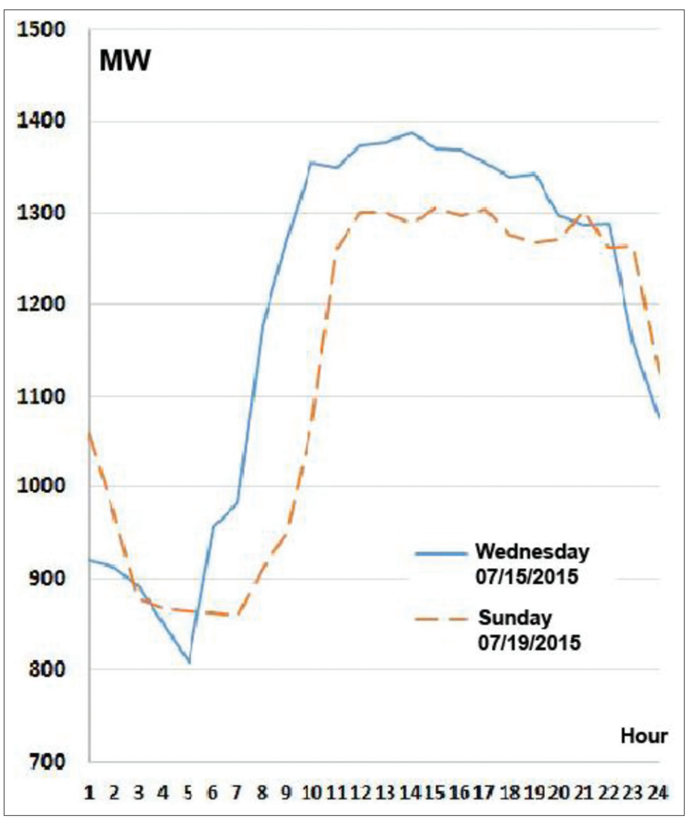
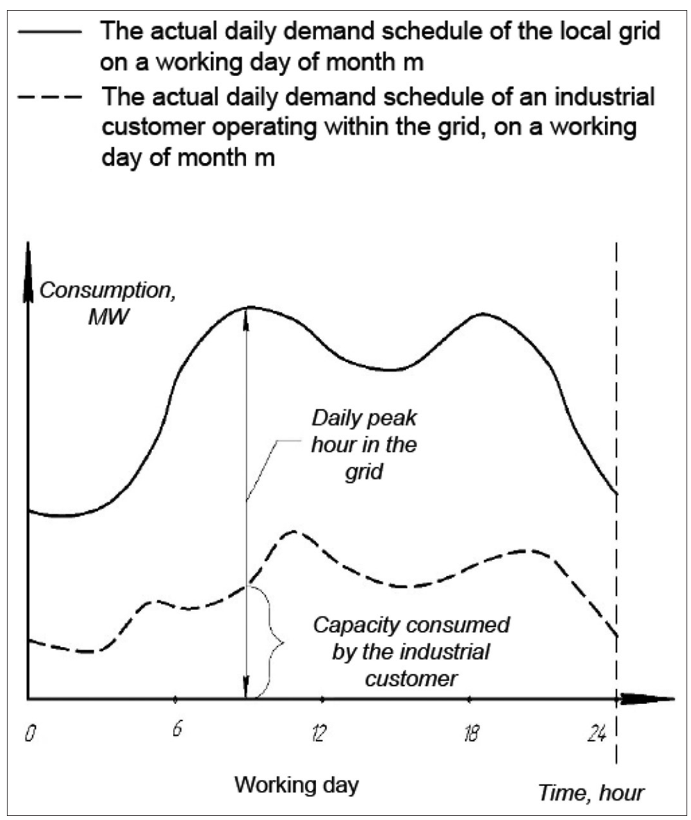


Figure 10: Example of the calculation of the industrial customer's obligation to pay for the capacity



where,

SP_m is the cost of the capacity purchased by an industrial customer in the month m

TP_m is the price of capacity purchased by an industrial customer in the month m

VP_m is the amount of obligation for the purchase of capacity of an industrial customer in the month m (4).

$$VP_m = \frac{\sum_{work\,d,m} W^t_{t\_\max\_region}}{n_{work\,d,m}} \quad \text{where } t = t\_max\_regio \qquad (4)$$

where,

W^t is the rate of electricity consumption by an industrial customer in hour t

t_max_region is the combined peak hour in a given region of Russia where the industrial customer purchases electricity in hour t on a working day of the month m

$n_{work\,d,m}$ is the number of working days in the month m.

$t\_max\_region \ni T\_peak\_SO$

T_peak_SO is intervals of the scheduled peak hours as approved by the System Operator of the Russian Grid.

$$\Delta SP_m = SP_m - SP'_m \qquad (5)$$

where,

ΔSP_m is the saving on capacity costs due to the price-based demand management

SP_m is the cost of paying for capacity before the application of price-based demand management

SP'_m is the cost of paying for capacity after the application of price-based demand management.

5.3. The Transmission Component

The amount of obligation to pay for transmission services is calculated each month. DSM of the transmission costs can only be accomplished if the industrial customers could choose a two-price tariff, which consists of the costs of maintaining transmission networks and the cost of technological losses.

The cost of technological losses does not depend on hourly load schedules, and their share in the total cost of transmission services does not exceed 20%.

The network maintenance costs are estimated for each participant according to hourly schedule of electricity consumption in a given month as the average hourly peak consumption of a given industrial customer during the scheduled peak hours on the working days (Figure 12).

Figure 5 shows an example of estimating the amount of obligation of an industrial customer to pay for network maintenance. As can be seen from the figure below, DSM is limited to the hours in the blue zone of the working days.

The price-dependent management of the hourly load schedule should consist in balancing the demand during periods of the

Figure 11: Monthly peak hour schedule 2018

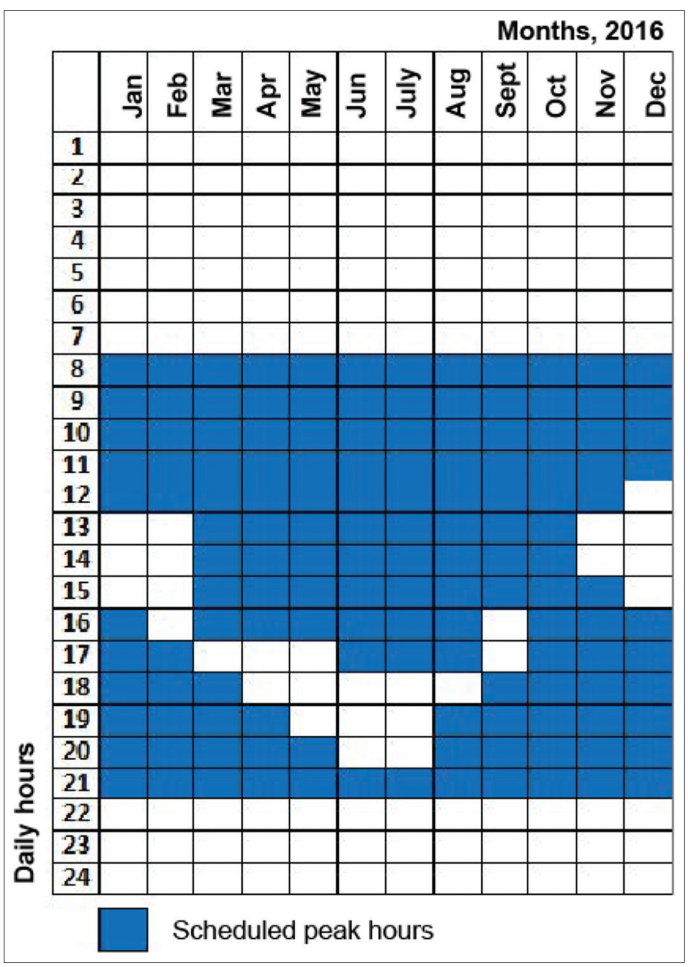
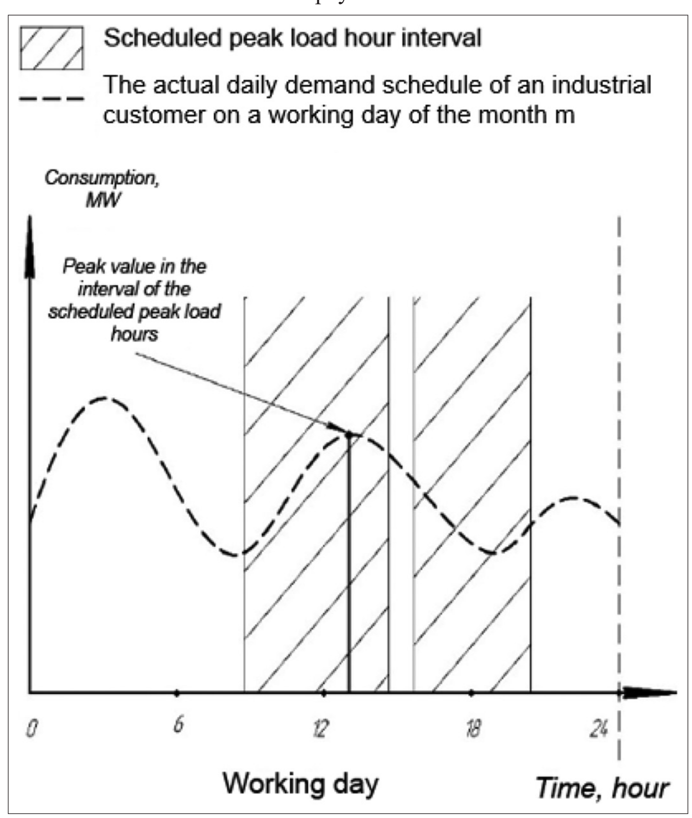


Figure 12: Example of estimating the amount of obligation of an industrial customer to pay for network maintenance



scheduled peak hours. It should be noted that the peak hour schedule is available to consumers 1 year in advance.

The price-based DSM will allow industrial customers to smooth out their consumption peaks and reduce the amount of obligations to pay for the transmission services. The transmission-related costs can be calculated using formulas (6-9), and the effect of the price-based DSM – by using formula (10).

$$ST2_m = ST2_m^{Maint} + ST2_m^{Loss} \tag{6}$$

where,

$ST2_m$ is the cost of electricity transmission services for an industrial customer at a two-price tariff in the month m

$ST2_m^{Maint}$ is the cost of electricity transmission services at a two-price tariff that takes into account the cost of network maintenance in the month m, (kW × month)

$ST2_m^{Loss}$ is the cost of electricity transmission services at a two-price tariff that takes into account the technological consumption (losses) in networks in the month m, (kW × h) (7).

$$ST2_m^{Maint} = T_m^{Maint} \times VT2_m \tag{7}$$

where,

T_m^{Maint} is the tariff rate for the maintenance of electric networks in the month m

$VT2m$ is the value adopted for calculating obligations for payment for the network maintenance, in the month m (8).

$$VT2_m = \sum_{work\,d,m} \max(W_{T\_peak\_SO}^t) \Big/ n_{work\,d,m} \tag{8}$$

where,

$\max(W_{T\_peak\_SO}^t)$ is the maximum consumption during the intervals of the scheduled peak hours T_peak_SO, approved by the Grid's system operator, for a working day of the month m (Figure 4) (9).

$$ST2_m^{Loss} = T_m^{Loss} \times \sum_m W \tag{9}$$

where,

T_m^{Loss} is the tariff rate for the payment of technological consumption (losses) in electric networks, in the month m

$\sum_m W$ is the total monthly electricity consumption in a given month.

$$\Delta ST2_m = ST2_m - ST2_m^{'} \tag{10}$$

where,

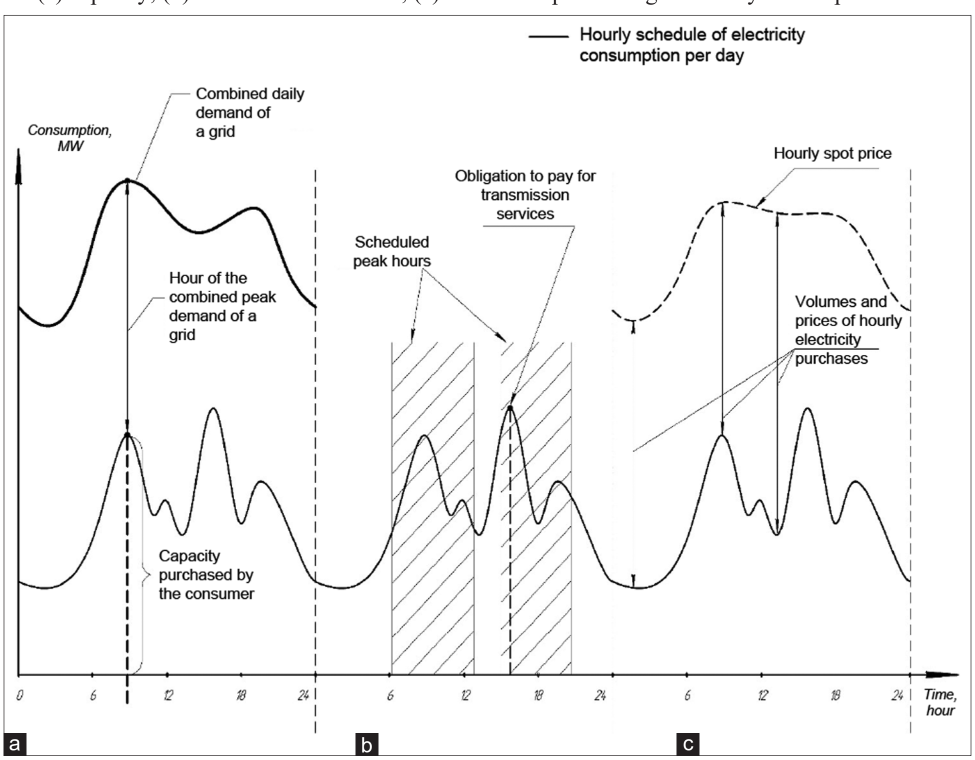
$\Delta ST2_m$ is the saving on transmission costs due to the price-based DSM

$ST2_m$ is the cost of paying for transmission services before the application of price-based DSM

$ST2_m^{'}$ is the cost of paying for transmission services after the application of price-based DSM.

It was found that all three components of the electricity price dependent the hourly daily consumption pattern and can therefore be managed on the side of the consumer (DSM) (11).

Figure 13: Graphic examples of estimating obligations to pay for different components of the electricity price based on a typical demand schedule (a) capacity; (b) transmission services; (c) the cost of purchasing electricity in the spot market



$$\begin{cases} S_m = (SP_m + SW_m + ST_m) \\ SP_m = f(W_m^t) \\ SW_m = f(W_m^t) \\ ST_m = f(W_m^t) \end{cases} \quad (11)$$

Figure 13 presents graphical examples of determining obligations to pay for various components of the electricity price based on a typical demand schedule. Graph A shows an example of estimating the cost of obligations to pay for capacity, Graph B – for transmission and Graph C – the cost of purchasing electricity on the spot market.

As can be seen from the example of the cost of obligation to pay for the capacity in Graph A, when applying DSM during the daily peaks of the grid's combined peak demand (4), the obligation to purchase capacity decreases for the customer of the electricity VP_m, and hence decreases the price of the capacity *SP* paid by the customer.

As seen from Graph B, DSM during the scheduled peak hours of the grid *T_peak_SO* (7) decreases the value adopted for calculation of obligation for payment for network maintenance $VT2_m$, and hence decreases the cost of transmission services paid by the consumer of electricity *S*П.

Also, as seen from Graph C, DSM during the periods of high spot prices P_{spot}^t (2) decreases the amount of electricity purchased at the maximum daily spot prices, and hence decreases the price of electricity purchased on the spot market *SW* by the consumer.

Therefore, DSM of all three components of the power price decreases the total cost of electricity *SE* purchased by consumers (9).

At the same time, a change in one price component, as a rule, entails a change in the other two components. This circumstance should be taken into account when optimizing the hourly schedule of electrical loads and making managerial decisions.

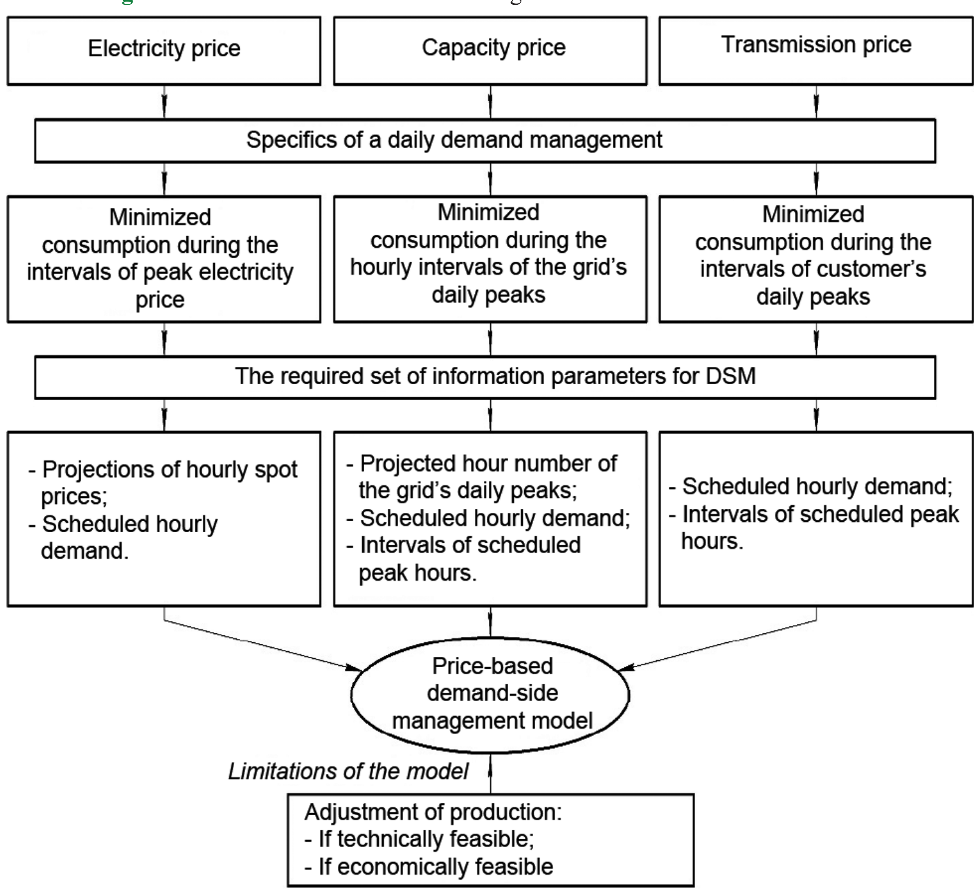
6. PRACTICAL APPLICATION

Based on the suggested approach to managing all three components of the power price, we have developed a price-based DSM model for industrial customers (Figure 14).

From our point of view, the calculation of the parameters used in the price-based DSM should be based not only on the demand and market indicators, but also take into account the technological and economic feasibility of adjusting the production processes which affect the hourly daily demand.

The application of the suggested price-based DSM model should be based on a large data array, which in turn puts forward stringent requirements for information support for the suggested approach.

Figure 14: Price-based demand-side management model for industrial customers



High data discreteness should be one of the key information requirements. Table 4 presents the requirements which we suggest with respect to the volume and discreteness of the data to be used in the suggested model.

We will illustrate the possible effects of managing the demand at one of the industrial customers in the Samara region. Figure 15 shows an example of an hourly daily demand curve of a machine manufacturer located in the Samara Region, before and after the DSM actions. The demand was adjusted during the customer's own demand peaks and reallocated to the hours when the demand is minimal.

Figure 15: Example of demand-side management at an industrial enterprise

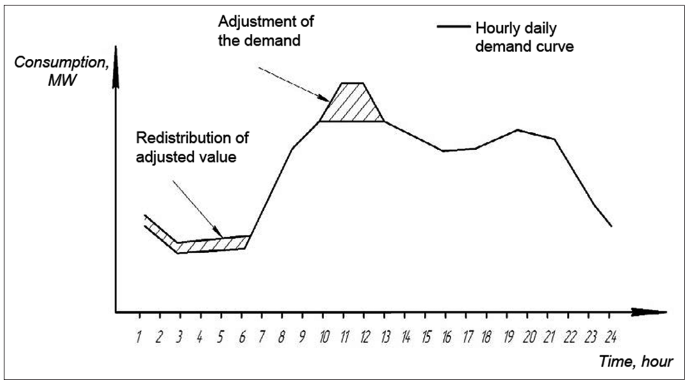


Table 4: Data required for the price-based demand-side management model

Indicator	Data discreteness, analysis depth
Actual power consumption	Hourly discreteness. Real-time analysis
Scheduled electricity consumption	Hourly discreteness. Value for the period from 1 day to 30 days in projection
Projected spot prices	Hourly discreteness. Value for the period from 1 day to 30 days in projection
Scheduled hours of the grid's daily peaks	1 h for 1 day. Value for the period from 1 day to 30 days in projection
Actual daily peak hours of the grid	1 h for 1 day
Intervals of the scheduled peak hours	The period for each day 30 days in projection
Actual production schedules	Hourly discreteness. Real-time analysis
Scheduled production processes	Hourly discreteness. Value for the period from 1 day to 30 days in projection

The initial value of power consumption at 11 and 12 h before the adjustment is 2.3 MW, after the adjustment – 2 MW. The redistribution to the minimum hours is 0.1 MW for periods from 1 to 6 h. Assuming similar loads in all days of December 2018, we calculated the cost of purchased electricity before and after the DSM adjustment and the effect of DSM (Table 5).

As can be seen from the calculation results, due to the DSM measure this industrial customer not only optimized its general demand curve, but also decreased its electricity purchase costs in December 2018 by 311,278 rubles, or 8.3%. In the annual terms, the economic effect can reach several million rubles, which – in the context of an economic crisis, cash deficits and the cost-saving urge – is a serious outcome achievable without any large-scale investment costs.

7. CONCLUSIONS

Our research suggests several important conclusions.

1. The growing global energy consumption along with the upward trend of all kinds of energy resources on world energy markets suggest the price of energy resources will continue to increase in the future
2. The implementation of an energy saving policy allows, without heavy investments, to give momentum to social and economic development at the national level
3. A comparative analysis of the indicators and dynamics of the projected and actual energy intensity of Russia's GDP shows that the country is lagging in terms of energy efficiency, which necessitates the search and implementation of new solutions
4. Electricity demand in different countries of the world demonstrates high volatility which has different parameters and manifests both in absolute terms and in terms of the annual, weekly and intraday volatility
5. DSM is an effective tool for improving energy efficiency that is used by many economies globally. DSM allows to gain economic effect at all levels of the economy
6. The identified benefits of DSM at different levels of the grid system and levels of the economy highlight the scale and effectiveness of DSM efforts

Table 5: Calculation of the economic effect of demand-side management of an industrial customer in the Samara region

Cost component	Before DSM			After DSM			Effect			
	Consumption	Cost In rubles	Tariff Rub/kWh	Consumption	Cost In rubles	Tariff Rub/kWh	Consumption	Cost In rubles	Tariff Rub/kWh	%
Electricity	1,103,600 kWh	1,310,778	1.188	1,103,600 kWh	1,302,827	1.181	0 kWh	–7951	-0.007	–0.6
Capacity	2.3 MW	883,216	0.800	2.0 MW	768,014	0.696	–0.3 MW	–115,202	–0.104	–13.0
Transmission (maintenance)	2.3 MW	1,442,292	1.307	2.0 MW	1,254,167	1.136	–0.3 MW	–188,125	–0.170	–13.0
Transmission (technological consumption)	1,103,600 kWh	97,911	0.089	1,103,600 kWh	97,911	0.089	0 kWh	0	0.000	0
Total	-	3,734,197	3.384	-	3,422,920	3.102	-	–311,278	–0.282	–8.3

DSM: Demand-side management

7. Demand response is at the core of any DSM model, with the economic rationing of the demand as its most effective component
8. Price-based consumption is at the core of a demand response model, and it can be implemented in case of discrete price setting of the electricity
9. The existing mechanisms of the wholesale and retail electricity markets in Russia enable industrial customers to independently reduce their costs for the purchase of electricity through price-based demand management
10. The suggested integrated model of the price-based DSM allows consumers to adjust their production and demand according to the supply prices and thus minimize their energy purchase costs.
11. The application of the price-based DSM model allows to comprehensively manage all existing components of the electricity price, translating into a significant economic effect for an industrial customer
12. The implementation of the price-based DSM model should be based on a large amount of information while also take into account the specifics of production and processes. The scale of an economic effect from the implementation of the suggested model emphasizes its scientific and practical importance
13. Demand specifics of Russia's regions and the existing mechanisms of the wholesale and retail electricity markets create a platform for the development and implementation of new solutions in the field of DSM and the entailing increase the energy efficiency of the Russian economy
14. The results of our study have high theoretical and practical importance which manifests in their potential application in the DSM-related decisions that are taken at the level of countries and territorial entities with a view to reducing energy consumption and improving energy efficiency.

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